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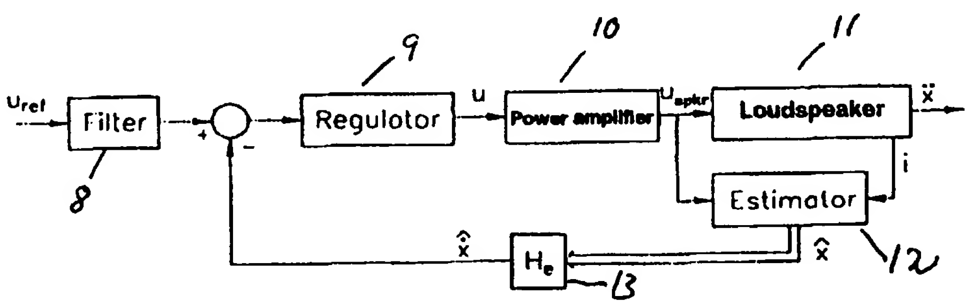
(54) Title: A METHOD OF CORRECTING NON-LINEAR TRANSFER BEHAVIOUR IN A LOUDSPEAKER



(57) Abstract

A method is disclosed in order to compensate for the non-linear transfer behaviour in a loudspeaker, comprising designing a model of the physical loudspeaker which is used in a non-linear estimator (12) (observer). The estimator receives the voltage across the moving coil of the loudspeaker and the current in the coil. These signal values are used for calculating an estimate which is fed to a differential unit having two inputs, the second one of which receives a desired signal. The difference between the two signals is fed to a controller (9) which then controls the current/voltage to the loudspeaker, optionally via an amplifier (10). The non-linear signal components of the loudspeaker may be limited hereby, which results in a significant reduction in the distortion in the loudspeaker. The estimator is designed such that it also allows for the dynamic variations which exist in the non-linear component parts of the loudspeaker, e.g. owing to changed temperature conditions.

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A method of correcting non-linear transfer behaviour in a loudspeaker

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The invention relates to a method of correcting non-linear transfer behaviour in a loudspeaker, wherein the moving coil of the loudspeaker is connected to a controller adapted to generate a signal for the moving coil to compensate the non-linear signal components which have occurred in the loudspeaker.

Musical sound systems have gone through a violent process of change during the last 10 to 20 years. Particularly because of the digital technology which has made it possible to construct excellent musical sound systems in which noise sources are essentially removed. Furthermore, the musical sound systems of today are of such a quality that non-linear signal parts are virtually eliminated.

The weakest part of a modern musical sound system is still the loudspeaker, however. Much effort has been devoted to the construction of loudspeakers which have the lowest possible distortion, and while this has been successful to a certain degree, it is well-known that loudspeakers loaded to a significant extent will distort the sound.

DE Offenlegungsschrift No. 4334040 discloses a loudspeaker structure whose non-linear transfer conditions are corrected by determining the physical variables of the loudspeaker on the basis of a measurement of the voltage across the moving coil and the current in it. This known manner of correcting non-linearities comprises a structure in which an adaptive linear or adaptive non-linear correction filter is connected to a detector coupling. The detector coupling emits a control signal from

the terminals of the moving coil, said control signal approximating the velocity of the moving coil. The output of the detector coupling is connected to an input of a differential amplifier, where a reference signal and the detector signal are compared to give an error signal on the output of the differential unit. This known system operates adaptively, as mentioned, which means that the system currently changes the model on the basis of which the error is calculated.

The object of the invention is to provide a structure in which non-linearities may be compensated with a very great accuracy in a loudspeaker by means of a simple circuit structure.

The object of the invention is achieved by a method of the type defined in the opening paragraph which is characterized in that the current and optionally the voltage across the moving coil of the loudspeaker are fed to two inputs of a non-linear estimator (observer), which represents a model of the linear and non-linear mechanical, acoustic and electrical properties of the loudspeaker, and that the estimator has an output which is fed to a differential unit which forms the difference between a desired signal fed to the loudspeaker and the output signal of the estimator, the differential signal being used as an input signal to the controller.

The use of a non-linear estimator representing a non-linear model of the loudspeaker provides the advantage that the correction of non-linearities may take place with a very great accuracy.

Further, when the estimator and the differential unit have interposed between them a selector circuit adapted to select a signal derived from the estimator and to

transfer this signal to the controller via the differential unit, advantages of circuitry are achieved since the selector unit may be adapted to feed a suitable signal to the controller, which will be easier to construct with the necessary circuitry.

Further, it is expedient if the derived signal is selected from the non-linear signal components from the estimator, since such a selection with good approximation can represent a correction signal capable of correcting the errors which originate from all non-linear components.

It is particularly expedient if the diaphragm velocity is selected as the derived signal component.

It is known in the operation of a loudspeaker that the non-linear transfer conditions of the loudspeaker change e.g. because of temperature changes in the moving coil and its windings.

Correction of the time variations and other differences between model and reality in the non-linear and linear transfer characteristic of the loudspeaker is provided according to the invention in that the current from the moving coil is fed to an additional differential unit having two inputs and one output, of which the first input receives the current from the moving coil of the loudspeaker and the second input receives a calculated estimated current, and in that the output of the additional differential unit is connected to a correction circuit adapted to transfer a correction signal to an additional input of the estimator.

According to the invention, the estimator describes a state function of the equation

$\dot{\hat{\underline{x}}} = \underline{\underline{F}}_{est}(\hat{\underline{x}}) \cdot \hat{\underline{x}} + \underline{G}_{est}(\hat{\underline{x}}) \cdot u_{spkr}$, where

$\underline{\underline{F}}_{est}(\hat{\underline{x}})$ represents the system matrix of the estimator

$\underline{G}_{est}(\hat{\underline{x}})$ represents the input vector of the estimator

$\hat{\underline{x}}$ represents the estimated state vector containing all estimated states - variables, and

u_{spkr} represents the voltage across the moving coil.

Further, it is noted that the notation " ˙ " throughout the formulae of the description indicates that the derived value is involved, while " ˆ " indicates that an estimated value is involved. Furthermore, "_" indicates that a vector is involved, while "=" indicates that a matrix is involved.

It is moreover expedient that the correction circuit of the estimator is a multiplier which performs the function

$\underline{L} \cdot \left(i - \underline{H}_{est}(\hat{\underline{x}}) \cdot \hat{\underline{x}}\right)$, where

$\underline{L}$ represents a correction vector,

$\underline{H}_{est}(\hat{\underline{x}})$ represents the output vector of the estimator.

To perform the correction also from the non-linear components which occur in an amplifier connected to a loudspeaker, it is an advantage if, as stated in claim 8, the input signal to the estimator is obtained from the series connection of an amplifier and the loudspeaker.

When the non-linear estimator and optionally other dynamics are implemented in a digital signal processor, a quick and a very accurate estimate of a desired physical quantity for controlling purposes may be obtained.

The invention will now be explained more fully below with reference to an example shown in the drawing, in which

fig. 1 shows a traditional loudspeaker illustrated with the most important constructional parts,

fig. 2 shows an example of how non-linearities can occur,

fig. 3 shows a first embodiment of the use of the invention,

fig. 4 shows a second embodiment of the use of the invention,

fig. 5 shows the structure of an estimator for use in the method of the invention,

fig. 6 schematically shows the effect of the principles of the invention.

As will be seen in fig. 1 illustrating a bass loudspeaker, said loudspeaker consists of a magnet 1 which is incorporated in a magnetic circuit which additionally contains an iron core 2 and an air gap 8. The air gap 8 accommodates an air coil 7 to which a diaphragm 4 is secured. The diaphragm 4 is moreover secured to a chassis 3 by means of the outer suspension 5. The air coil 7 and the diaphragm 4 are additionally secured to/controlled by an inner suspension 6.

A strong magnetic field is formed in the air gap 8 in which the air coil 7 is positioned, so that when the coil is positioned in said field, electrical energy may be converted into mechanical energy by feeding a current through the coil. The diaphragm 4, which is secured to the coil, as mentioned, is the sound-producing element

which converts the electrical energy from the moving coil to the air.

Fig. 2 shows two positions of the coil 7 in the air gap 8. It is shown in the centre of the figure that the coil is entirely surrounded by the air gap, while to the right in fig. 2 it is positioned somewhat outside the air gap , corresponding to the application of a force to the diaphragm. As will be explained later, the force produced when a current is passed through the coil, depends non-linearly on the current, because the magnetic flux is not homogeneous at the outer edges of the iron of the core.

In fig. 3 the numeral 8 designates a filter which is a so-called equalizing filter that alters the frequency response to the desired one. The output of the filter 8 is coupled to the input of a differential unit whose output is coupled to a controller 9, which is additionally connected in series with a power amplifier 10 and a loudspeaker 11. The moving coil (not shown) of the loudspeaker 11 is connected to an estimator 12, which receives partly the voltage across the moving coil u_{spkr} and partly the current i in the moving coil. An output of the estimator 12 is connected to a selector 13 adapted to provide, on the basis of the signals from the estimator, a suitable signal which may be fed to the differential unit, whose output terminal is connected to the controller 9.

To illustrate the principles of the invention, it will be explained below how the electrical and mechanical properties of a loudspeaker may be described.

This is done by a state equation and an output equation, respectively.

The state equation may be expressed as follows:

$$\dot{X} = \underline{\underline{F}}(x)\cdot\underline{x} + \underline{G}(x)\cdot u_{spkr}$$

where $\underline{\underline{F}}(\underline{x})$ represents the non-linear system matrix in the loudspeaker model,

$\underline{G}(\underline{x})$ represents a possible non-linear vector,

$\underline{x}$ represents the state vector in the loudspeaker model which contains all state variables,

u_{high} represents the voltage across the moving coil in the loudspeaker.

This may also be expressed by the following formula for a selected loudspeaker (the embodiment of fig. 3):

$$\underbrace{\begin{bmatrix}\dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{bmatrix}}_{\dot{\underline{x}}} = \underbrace{\begin{bmatrix}-\frac{R}{L} & -\frac{Bl(x_4)}{L} & 0\\ \frac{Bl(x_4)}{m} & -\frac{r}{m} & -\frac{k}{m}\\ 0 & 1 & 0\end{bmatrix}}_{\underline{\underline{F}}(\underline{x})}\cdot\underbrace{\begin{bmatrix}x_2\\ x_3\\ x_4\end{bmatrix}}_{\underline{x}} + \underbrace{\begin{bmatrix}\frac{1}{L}\\ 0\\ 0\end{bmatrix}}_{\underline{G}(\underline{x})}\cdot u_{spkr}$$

x2 represents the current i in the moving coil,

x3 represents the diaphragm velocity $\dot{x}$

x4 represents the diaphragm position x,

L represents the inductance in the moving coil,

R represents the ohmic resistance in the moving coil,

Bl(x4) represents the force factor on the diaphragm as a function of the diaphragm position,

k represents a spring constant,

r represents a coefficient of friction, and

m represents the mass of the moving parts of the loudspeaker and the mass of the air which is moved.

The output equation may be expressed by the formula

$y = \underline{H}(\underline{x}) \cdot \underline{x} + J(\underline{x}) \cdot u_{spkr}$

where $\underline{H}(\underline{x})$ represents a non-linear output vector,

$J(\underline{x})$ represents a forward factor and u_{spkr} represents the voltage across the moving coil in the loudspeaker.

It can be shown that the output equation may be written as follows (the embodiment of fig. 3):

$$y = \underbrace{\begin{bmatrix} \frac{Bl(x_4)}{m} & -\frac{r}{m} & -\frac{k}{m} \end{bmatrix}}_{\underline{H}(\underline{x})} \cdot \underbrace{\begin{bmatrix} x_2 \\ x_3 \\ x_4 \end{bmatrix}}_{\underline{x}} + \underbrace{[0]}_{J(\underline{x})} \cdot u_{spkr}$$

where the constituent variables represent the same as in the state equation.

It is now possible to design the estimator 12 in fig. 3 by means of the above equations so that it is an approximated copy of the physical loudspeaker 11.

Fig. 4 shows an embodiment in which also the non-linearities of the power amplifier are incorporated in the estimator calculation of the signal which is fed to the controller, it being then possible to express the state equation as follows:

$$\underbrace{\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x} \end{bmatrix}}_{\dot{\underline{x}}} = \underbrace{\begin{bmatrix} -12{,}6 & 0 & 0 & 0 \\ -\dfrac{12{,}6}{L} & -\dfrac{R}{L} & -\dfrac{Bl(x_4)}{L} & 0 \\ 0 & \dfrac{Bl(x_4)}{m} & -\dfrac{r}{m} & -\dfrac{k}{m} \\ 0 & 0 & 1 & 0 \end{bmatrix}} \cdot \underbrace{\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}}_{\underline{x}} + \underbrace{\begin{bmatrix} 1 \\ \dfrac{1}{L} \\ 0 \\ 0 \end{bmatrix}}_{\underline{G(x)}} \cdot u_{spkr}$$

where x_1 represents the integral of the voltage across the loudspeaker, while the other variables have the same meaning as in the embodiment of fig. 3.

In this case, the state equation may be expressed as follows:

$$y = \underbrace{\begin{bmatrix} 0 & \dfrac{Bl(x_4)}{m} & -\frac{r}{m} & -\frac{k}{m} \end{bmatrix}}_{\underline{H}(\underline{x})} \cdot \underbrace{\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}}_{\underline{x}} + \underbrace{[0]}_{J(\underline{x})} \cdot u_{spkr}$$

where the constituent variables represent the same as before.

Fig. 5 is a more detailed view of the estimator connected to a physical loudspeaker 11, and additionally shows a vector 19 which is intended to measure the current in the moving coil. The estimator may mathematically be expressed in the following manner:

$$\dot{\underline{\hat{x}}} = \underline{\underline{F}}_{est}(\underline{\hat{x}}) + \underline{G}_{est}(\underline{\hat{x}}) \cdot u_{spk_r} + \underline{L} \cdot \left(i - \underline{H}_{est}(\underline{\hat{x}}) \cdot \underline{\hat{x}}\right)$$

In this formula $\underline{\underline{F}}_{est}(\underline{\hat{x}})$ represents the system matrix in the estimator,

$\underline{G}_{est}(\underline{\hat{x}})$ represents the input vector of the estimator, $\underline{L}$ represents a correction vector,

$\underline{H}_{est}(\underline{\hat{x}})$ represents the output vector of the estimator, and

$\underline{\hat{x}}$ represents the estimated state vector containing all estimated states.

It is noted that the last term of the above equation,

$$\underline{L} \cdot (i - \underline{H}_{est}(\underline{\hat{x}}) \cdot \underline{\hat{x}})$$

where $\underline{L}$ represents a correction vector,

is an indication of the correcting nature of the estimator whose dynamics are determined by $\underline{L}$.

Thus, constant correction in the estimator on the basis of the difference between measured and estimated currents results in an estimator design which constantly approximates reality, i.e. the physical loudspeaker.

As will be seen in fig. 5, 18 designates a circuit in which the dynamic conditions in the physical loudspeaker are reflected. The signal from the circuit 18 is thus used for adjusting the time variations in the estimator.

It will be explained briefly below how the estimator of the invention operates.

As already mentioned, the essential aspect of the invention is to provide a non-linear model of the physical loudspeaker where the most important non-linearities are included. The force vector, Bl(x), is always included as

a function of the diaphragm position x, since this non-linearity is the most important one. The estimator receives the same input signal u_{spkr} as the physical loudspeaker, on the basis of which an estimate of the current in the moving coil called $\hat{i}$ is estimated. The estimate is compared with the real current i which is measured in a known manner. By subtracting the two currents $\hat{i}$ and i from each other, an error of the estimate of the current is calculated, and this error is then multiplied by a suitable vector $\underline{L}$ and is afterwards fed back to the loudspeaker model as a correction contribution. In the same manner, the estimator constantly tries to achieve a good estimate of the real current in the loudspeaker. The most interesting thing about these circumstances is that if the estimate of the current is good, and the factors in the vector $\underline{L}$ are selected correctly, the other quantities in the loudspeaker model will likewise follow the corresponding physical quantities in the loudspeaker. In other words, e.g. the diaphragm velocity $\dot{x}$ may be found merely by correcting the estimator according to the current in the moving coil. The longer the loudspeaker has been in operation, the more its dynamics are changed significantly, which, however, does not change the precision of e.g. the estimated diaphragm velocity $\dot{x}$ considerably, as the estimator compensates for this significant change in the physical loudspeaker. These circumstances are illustrated in fig. 6, where the line "estimated variable" follows the line "true variable" closer than the line "was in loudspeaker model". It is noted in this connection that the line "estimated variable" is not to illustrate that the distance between the lines "true variable" and "estimated variable" becomes greater as a function of time.

Although the invention has been explained in connection with the correction of non-linear transfer conditions in

a loudspeaker, nothing prevents the principles of the invention from being generally applied in circuitry which is non-linear by nature and in which linearization is desired.

The decisive thing is that a dynamic model of the non-linear circuit may be designed, and that one or more characteristic physical quantities of the non-linear circuit can be measured. By drafting a state function for the estimator which includes one or more physical variables for the non-linear circuit and drafting an output equation for the non-linear circuit, it is possible to design the estimator such that the output of the non-linear circuit is linearized in connection with various types of control circuits.

Examples of this include feedforward circuits, cascade control, state-space control/designs and the like.

P a t e n t   C l a i m s :

1. A method of correcting non-linear transfer behaviour in a loudspeaker, wherein the moving coil (7) of the loudspeaker is connected to a controller (9) and a power amplifier (10) adapted to provide a signal to the moving coil (7) to limit the non-linear signal components which have occurred in the loudspeaker, c h a r a c t e r - i z e d in that the current in and optionally the voltage (u_{spkr}) across the moving coil (7) of the loudspeaker are fed to separate inputs of an estimator (12), which is built around a non-linear model circuit of the linear and non-linear mechanical, acoustic and electrical properties of the loudspeaker, and that the estimator (12) has an output which is fed to a differential unit which forms the difference between a desired signal fed to the loudspeaker and the output signal of the estimator, the differential signal being used as an input signal to the controller (9).

2. A method according to claim 1, c h a r a c t e r - i z e d in that a selector circuit (13) is additionally arranged between the estimator and the differential unit, said selector circuit being adapted to select a signal derived from the estimator and to transfer this signal to the controller via the differential unit.

3. A method according to claim 2, c h a r a c t e r - i z e d in that the derived signal is selected from the non-linear signal components from the estimator.

4. A method according to claim 3, c h a r a c t e r - i z e d in that the diaphragm velocity is selected as the non-linear signal component.

5. A method according to claims 1-4, c h a r a c t e r - i z e d in that the current (i) from the moving coil (7) is fed to an additional differential unit (20) having two inputs and one output, of which the first input receives the current from the moving coil of the loudspeaker and the second input receives the estimated current, and that the output of the additional differential unit is connected to a correction circuit adapted to transfer a correction signal to an additional input of the estimator.

6. A method according to claim 1, c h a r a c t e r - i z e d in that the estimator describes a state function of the formula

$$\dot{\underline{\hat{x}}} = \underline{\underline{F}}_{est}(\underline{\hat{x}}) \cdot \underline{\hat{x}} + \underline{G}_{est}(\underline{\hat{x}}) \cdot u_{spkr}$$

where $\underline{\hat{x}}$ represents the estimated state vector containing all estimated variables,

$\underline{\underline{F}}_{est}(\underline{\hat{x}})$ represents the system matrix of the estimator,

$\underline{G}_{est}(\underline{\hat{x}})$ represents the input vector of the estimator, and

u_{spkr} the voltage across the moving coil of the loudspeaker.

7. A method according to claim 1, c h a r a c t e r - i z e d in that the correction circuit (18) of the estimator (12) is a multiplier which performs the function

$$\underline{L} \cdot (i - \underline{H}_{est}(\underline{\hat{x}}) \cdot \underline{\hat{x}})$$

where $\underline{L}$ represents a correction vector, i represents the current in the moving coil of the loudspeaker,

$\underline{\hat{x}}$ represents the estimated state vector, and

$\underline{H}_{est}(\hat{\underline{x}})$ represents the output vector which multiplied by the state vector in the estimator ensures that the estimator is corrected correctly according to $i - \hat{i}$.

8. A method according to any one of the preceding claims, characterized in that the input signal to the estimator is obtained from the series connection of an amplifier and the loudspeaker.

9. A method according to any one of the preceding claims, characterized in that a digital signal processor is used as the estimator.

10. A method according to any one of the preceding claims, characterized in that a bass loudspeaker is used as the loudspeaker.

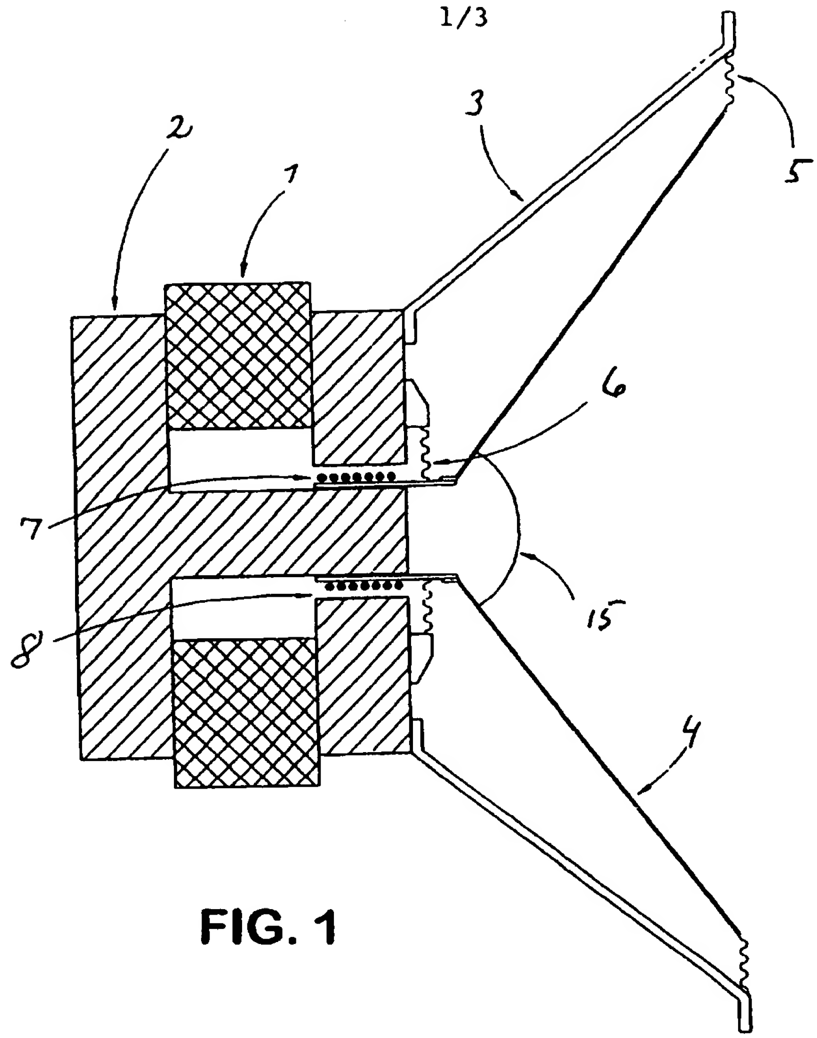

FIG. 1

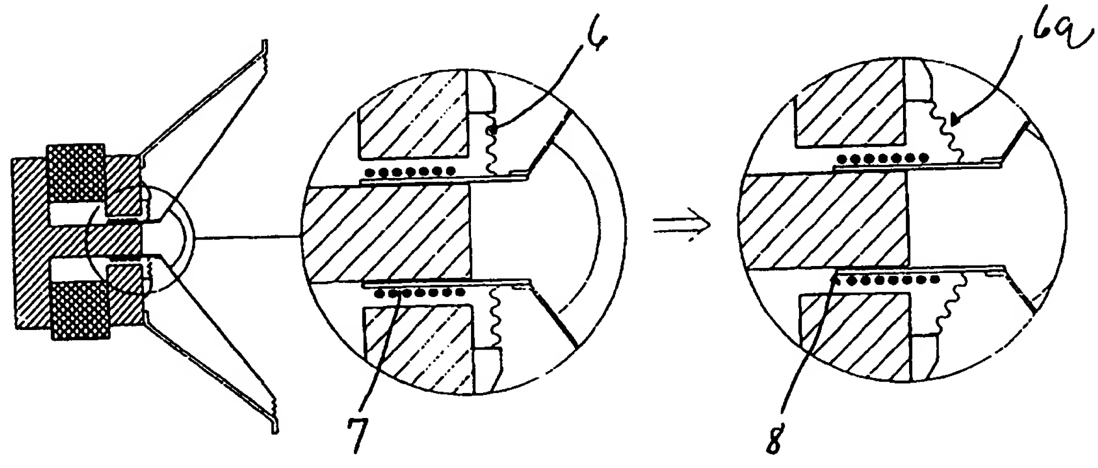

FIG.2

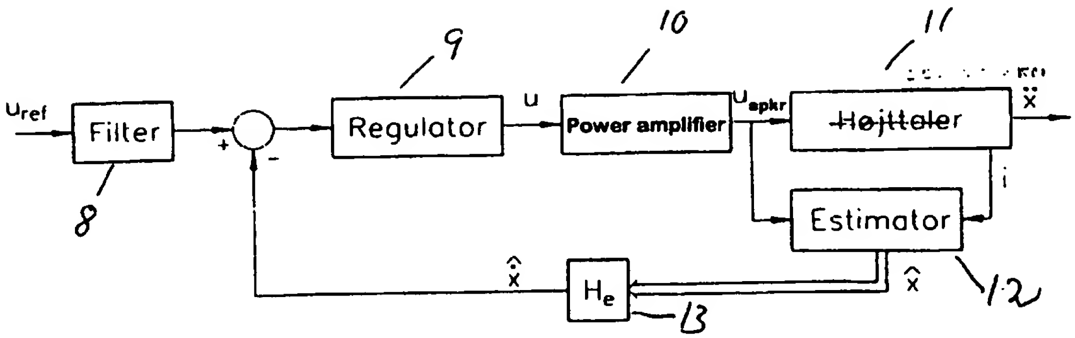

FIG. 3

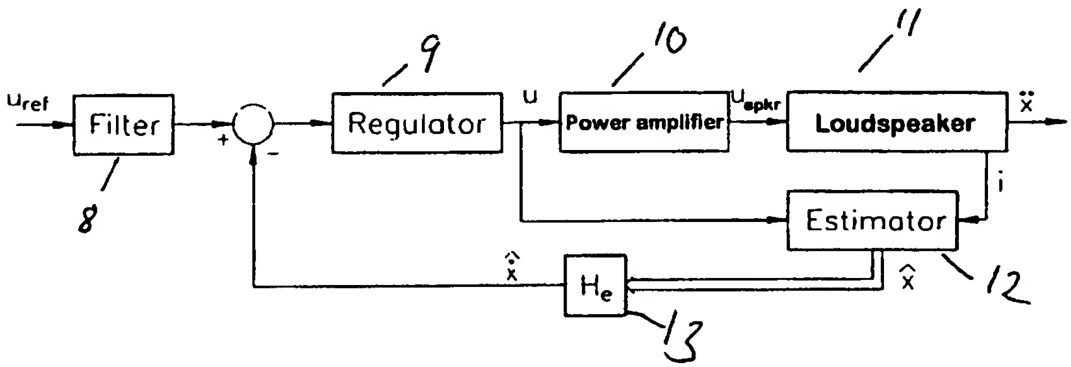

FIG. 4

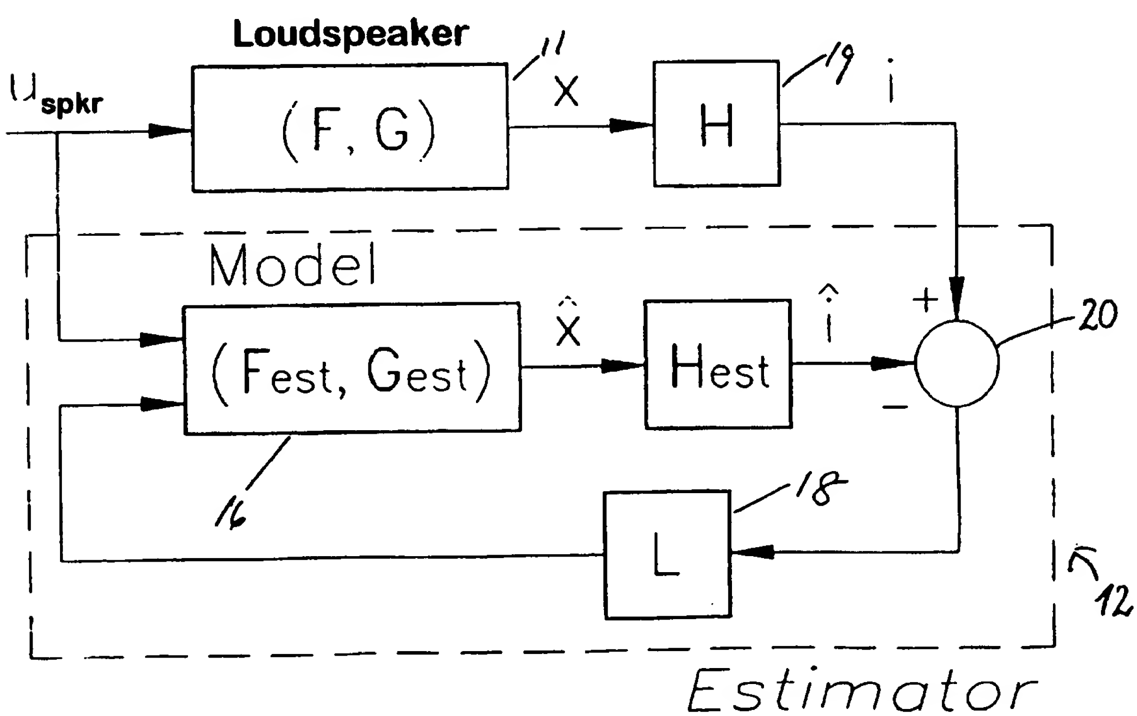

FIG. 5

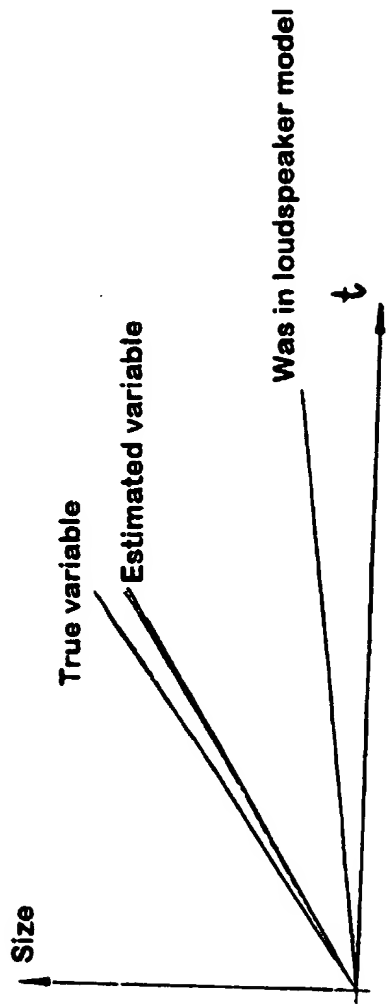
Was in loudspeaker model
t
Estimated variable
True variable
Size

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/DK 97/00012

A. CLASSIFICATION OF SUBJECT MATTER

IPC6: H04R 3/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4709391 A (KAIZER ET AL), 24 November 1987 (24.11.87) --	1-10
A	US 5438625 A (KLIPPEL), 1 August 1995 (01.08.95) --	1-10
A	US 5226089 A (YOON ET AL), 6 July 1993 (06.07.93) --	1-10
A	US 5068903 A (WALKER), 26 November 1991 (26.11.91) --	1-10
A	US 5542001 A (REIFFIN), 30 July 1996 (30.07.96) -- --------	1-10

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

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